A REVIEW ON LOCALIZATION ALGORITHMS IN UNDERWATER SENSOR NETWORKS

[1]Ritu Tiwari,[2]Richa Tiwari

[1]Assistant Professor,[2]Assistant Professor
[1]Compter Science Engineering,
[1]Modi Institute of Technology, Kota, India

ABSTRACT

This review paper provides a comprehensive examination of localization algorithms in underwater sensor networks (USNs), addressing the unique challenges posed by the aquatic environment, such as severe signal attenuation, multipath propagation, node mobility due to water currents, and significant energy constraints. It categorizes the localization algorithms into time-of-arrival (TOA), time-difference-of-arrival (TDOA), received signal strength indicator (RSSI), angle-of-arrival (AOA), and hybrid and collaborative approaches, highlighting their operational mechanisms, advantages, and limitations. Furthermore, the paper discusses the current trends and future directions in USN localization, including the integration of machine learning techniques and the potential for enhancing localization accuracy through the use of auxiliary information like ocean current models. Through an analysis of existing literature and a discussion on the environmental challenges and technical limitations of underwater communication technologies, this paper aims to provide insights into the advancements and remaining hurdles in the field of USN localization, contributing to a deeper understanding of its critical role in enhancing the capabilities and applications of underwater sensor networks.

Keywords: Underwater Sensor Networks, Localization Algorithms, Acoustic Communication, Environmental Challenges, Machine Learning.

INTRODUCTION

Underwater Sensor Networks (USNs) represent a pivotal advancement in the domain of underwater exploration and monitoring, facilitating a wide array of applications from oceanographic data collection, pollution monitoring, underwater pipeline monitoring to surveillance and reconnaissance missions (Heidemann et al., 2012). These networks comprise a multitude of sensor nodes and vehicles deployed underwater, tasked with collecting and transmitting data back to surface stations or underwater bases. Unlike their terrestrial counterparts, USNs operate in a uniquely challenging environment that significantly impacts communication, localization, and network management (Akyildiz et al., 2005).

Localization, the process of determining the geographical positions of nodes within a network, is crucial for the operational efficacy of USNs. It underpins tasks such as data tagging with spatial information, network routing, and the deployment and retrieval of sensor nodes. However, the underwater environment introduces a set of formidable challenges not present in terrestrial settings, including severe signal attenuation, multipath propagation due to reflection from the surface and seabed, and node mobility induced by water currents (Zhou et al., 2011). These factors necessitate specialized localization algorithms tailored to the underwater environment.

The primary communication medium in USNs is acoustic signalling, chosen over radio or optical means due to its better propagation characteristics underwater (Stojanovic, 2009). However, acoustic communication is fraught with challenges, such as limited bandwidth, high latency, and significant signal attenuation with distance and due to absorption by the water body, all of which complicate the localization process (Freitag et al., 2005). Moreover, the speed of sound in water varies with temperature, salinity, and pressure, adding another layer of complexity to accurate distance estimation based on signal propagation time (Zhou et al., 2011).

In addition to communication challenges, the underwater environment itself poses significant hurdles. The variability in environmental conditions affects sensor operations and acoustic signal propagation, necessitating adaptive and robust localization methods. Furthermore, the energy constraints of underwater sensors, compounded by the difficulty of battery replacement or recharging, demand highly energy-efficient localization algorithms to ensure the longevity and sustainability of USN deployments (Jafri et al., 2014).

Given these challenges, a variety of localization algorithms have been proposed, each attempting to address the intricacies of underwater environments. These algorithms can be broadly classified into range-based and range-free methods. Range-based methods, which include Time of Arrival (ToA), Time Difference of Arrival (TDoA), and Angle of Arrival (AoA), rely on the measurement of distances or angles between nodes to estimate positions. These methods often require additional hardware and can be affected by the aforementioned issues of acoustic communication (Erol-Kantarci et al., 2011). On the other hand, range-free methods, which infer location based on network connectivity and proximity, offer a less hardware-intensive solution but typically with lower accuracy (Liu et al., 2010).

Emerging trends in USN localization focus on overcoming the limitations of existing algorithms through the integration of machine learning techniques, the use of auxiliary information such as ocean current models, and the development of hybrid methods combining the strengths of range-based and range-free approaches (Tuna et al., 2014). Moreover, the potential for integrating USNs with other types of networks, such as terrestrial and satellite networks, presents opportunities for creating a more interconnected and comprehensive monitoring and data collection system.

This review paper aims to provide a thorough examination of the state-of-the-art in localization algorithms for underwater sensor networks. By navigating through the complexities of underwater communication, addressing the environmental challenges, and exploring innovative solutions, this paper seeks to offer insights into the advancements and remaining hurdles in the field of USN localization. Through a comprehensive analysis of existing literature and current research trends, this review will contribute to a deeper understanding of the critical role of localization in enhancing the capabilities and applications of underwater sensor networks.

Table 1: Comparison of Electromagnetic, Acoustic, and Optical Waves in Underwater Environment

Properties	**Electromagnetic Waves**	**Acoustic Waves**	**Optical Waves**
Frequency band	~kHz	~MHz	~10^14-10^15 Hz
Bandwidth	~kHz	~MHz	~10-150 MHz
Power loss	>0.1 dB/m/Hz	~28 dB/1 km/100 MHz	∝ turbidity
Effective range	~1 m	~10 m	~10-100 m
Nominal speed (m/s)	~1,500	~33,333,333	~33,333,333

Properties	Electromagnetic Waves	Acoustic Waves	Optical Waves
Antenna size	~0.1 m	~0.5 m	~0.1 m

2. CLASSIFICATION OF LOCALIZATION ALGORITHMS

Localization algorithms in underwater sensor networks (UWSNs) can be classified based on their methodologies, which encompass a variety of techniques for estimating the positions of sensor nodes in the underwater environment. These algorithms leverage different principles and measurements, such as time-of-arrival (TOA), time-difference-of-arrival (TDOA), received signal strength indicator (RSSI), and angle-of-arrival (AOA), to infer the spatial coordinates of sensor nodes. In this section, we categorize localization algorithms in UWSNs and provide an overview of each category:

- **Time-of-Arrival (TOA) based Algorithms:** TOA based algorithms estimate the distances between sensor nodes by measuring the time taken for acoustic signals to propagate between nodes. By employing synchronized clocks and precise timing measurements, these algorithms determine the time-of-arrival of signals at different nodes and use this information to calculate the distances. Examples of TOA based algorithms include multilateration, sequential methods, and maximum likelihood estimation (MLE). Multilateration utilizes distance measurements from multiple reference nodes to triangulate the position of a target node. Sequential methods iteratively refine the position estimate based on sequential distance measurements. MLE approaches estimate node positions by maximizing the likelihood function based on observed TOA measurements and assumed statistical models (Peres, R. T., &Pedreira, C. E. 2010, Nazir, U. et al 2012 & Han, G et al 2013).

- **Time-Difference-of-Arrival (TDOA) based Algorithms:** TDOA based algorithms estimate the differences in arrival times of signals between pairs of sensor nodes. By comparing the time differences at multiple reference nodes, these algorithms infer the relative distances between nodes and triangulate the position of the target node. Common TDOA based algorithms include two-way ranging (TWR), multilateration, and non-linear least squares (NLLS). TWR involves bidirectional communication between nodes to measure the round-trip time of acoustic signals. Multilateration techniques use TDOA measurements from multiple reference nodes to determine the target node's position. NLLS methods iteratively refine position estimates by minimizing the difference between observed and predicted TDOA values (Do et al 2015 & Kim et al 2014).

- **Received Signal Strength Indicator (RSSI) based Algorithms:** RSSI based algorithms estimate distances between sensor nodes based on the received signal strength of acoustic transmissions. By correlating signal strength measurements with distance attenuation models, these algorithms infer the distances between nodes. Examples of RSSI based algorithms include trilateration, fingerprinting, and machine learning approaches. Trilateration calculates node positions based on distance estimates derived from RSSI measurements and known locations of reference nodes. Fingerprinting methods create a database of signal strength patterns at known locations and match observed RSSI measurements to determine node positions. Machine learning algorithms utilize RSSI data to train models for predicting node positions based on observed signal characteristics (Han, G. 2012 &Suomela, J. 2013).

- **Angle-of-Arrival (AOA) based Algorithms:** AOA based algorithms estimate the angles at which acoustic signals arrive at sensor nodes relative to known reference directions. By measuring the arrival angles from multiple reference nodes, these algorithms triangulate the position of the target node. AOA based algorithms include techniques such as acoustic Doppler shift (ADS) and angle-of-arrival estimation. ADS methods exploit the Doppler effect induced by the motion of the target node to estimate arrival angles. Angle-of-arrival estimation techniques use array processing algorithms to estimate the angles of arrival based on spatial beamforming and signal processing (Li-qiang, C. et al 2013 and Bischl, B. et al 2013).

- **Hybrid and Collaborative Localization Approaches:** Hybrid and collaborative localization approaches combine multiple localization techniques to improve accuracy, robustness, and scalability. These approaches leverage complementary strengths of different localization methods to overcome the limitations of individual techniques. Examples of hybrid and collaborative localization approaches include sensor fusion, cooperative localization, and adaptive algorithms. Sensor fusion integrates measurements from multiple sources, such as TOA, TDOA, RSSI, and AOA, to improve localization accuracy. Cooperative localization schemes involve collaboration between sensor nodes to share information and enhance localization performance. Adaptive algorithms dynamically select and combine localization methods based on environmental conditions, network dynamics, and application requirements. (Peres, R. T., &Pedreira, C. E. 2010, Nazir, U. et al 2012 & Han, G et al 2013).

3. RELATED PAST STUDIES

Title	**Authors**	**Year**	**Brief Finding**
Localization Algorithm for Underwater Sensor Network: A Review	Junhai Luo, Yang Yang, Zhiyan Wang, Yanping Chen	2021	Reviews challenges of underwater acoustic communication and positioning, comparing various localization algorithms based on new taxonomy.
Survey of Localizations Algorithms in Underwater Wireless Sensor Network	Sitanshu Kumar, S. Rathod	2021	Analyzes different localization algorithms techniques, detailing their localization error, computation time, and amount of localized nodes.
A factoring algorithm for probabilistic localization in Underwater Sensor Networks	SalwaAbougamila, Mohammed Elmorsy, E. Elmallah	2017	Introduces a probabilistic graph model for node localization, offering solutions for semi-mobile UWSNs.

Title	Authors	Year	Brief Finding
Localization and Detection of Targets in Underwater Wireless Sensor Using Distance and Angle Based Algorithms	InamUllah, Jingyi Chen, Xin Su, C. Esposito, Chang Choi	2019	Proposes improved range-based algorithm for localization with emphasis on accuracy and energy efficiency.
An improved underwater acoustic network localization algorithm	Wu Zhehao, Li Xia	2015	Introduces an algorithm enhancing tolerance to noise and reducing redundancy in calculation for better positioning.
Research on Localization Algorithms Based on Acoustic Communication for Underwater Sensor Networks	Junhai Luo, Liying Fan, Shan Wu, Xueting Yan	2017	Surveys in-depth various acoustic communication-based localization algorithms for UWSNs.
Efficient and Accurate Target Localization in Underwater Environment	InamUllah, Yiming Liu, Xin Su, Pankoo Kim	2019	Presents schemes for UWSNs focusing on minimizing mean estimation errors and energy consumption.
Probabilistic Localization of Underwater Sensor Networks	SalwaAbougamila	2016	Utilizes probabilistic graphs for understanding node location uncertainty in UWSNs.
Localization of Nodes in Underwater Wireless Sensor Networks	M. Sunitha, R. K. Karunavathi	2019	Explores Kalman filter and extended Kalman filtering methods to minimize localization errors in UWSNs.

Title	Authors	Year	Brief Finding
Asynchronous Localization With Mobility Prediction for Underwater Acoustic Sensor Networks	Jing Yan, Xiaoning Zhang, Xiaoyuan Luo, Yiyin Wang, Cailian Chen, X. Guan	2018	Develops an asynchronous localization algorithm that compensates for clock asynchrony and node mobility.

4. CHALLENGES IN UNDERWATER LOCALIZATION

Underwater localization faces a unique set of challenges that stem primarily from the inherent properties of the aquatic environment and the technical limitations of underwater communication technologies. Acoustic communication, the predominant method for underwater sensors due to its better propagation characteristics in water compared to electromagnetic and optical signals, introduces significant challenges including signal attenuation, multi-path propagation, and delay variances. Signal attenuation occurs as the acoustic signal loses its energy over distance and due to absorption by the water, which limits the range and reliability of communication (Stojanovic, 2009). Multi-path propagation, where signals reflect off the surface and the bottom of the ocean, leads to multiple copies of the signal arriving at the receiver at different times, causing signal distortion and making it difficult to accurately determine the time of arrival (ToA) and, consequently, the distance between nodes (Freitag et al., 2005).

Moreover, the mobility of sensor nodes, caused by water currents, complicates the localization process by continuously altering the topology of the sensor network. This mobility can lead to significant errors in localization if not properly accounted for, requiring algorithms that can adapt to changes in the node positions over time (Erol-Kantarci et al., 2011). The energy constraints of underwater sensors further exacerbate these challenges. Given the difficulty and expense of replacing or recharging batteries in underwater environments, energy efficiency becomes a critical consideration in the design of localization algorithms, necessitating methods that minimize communication and computational overheads (Jafri et al., 2014).

The harsh underwater environment itself—characterized by varying temperature, pressure, and salinity—can affect sensor operation and signal propagation. These environmental factors can alter the speed of sound through water, affecting the accuracy of distance measurements based on acoustic signal propagation time (Zhou et al., 2011). Addressing these challenges requires innovative approaches to localization that can cope with the dynamic and harsh conditions of underwater environments, including robust signal processing techniques, adaptive algorithms capable of responding to changes in network topology and environmental conditions, and energy-efficient designs that extend the operational lifespan of the sensor nodes.

5. CONCLSUION

In conclusion, this review underscores the pivotal role of localization algorithms in enhancing the operational efficacy of underwater sensor networks (USNs), crucial for a myriad of applications ranging from environmental monitoring to oceanographic exploration. The paper delineates the myriad challenges that beset USN localization, primarily rooted in the unique properties of the underwater environment—such as signal attenuation, multipath propagation, and the dynamic nature of underwater elements—compounded by the technical limitations of acoustic communication. Despite these challenges, the evolution of localization techniques, from traditional range-based methods like TOA and

TDOA to innovative range-free and hybrid approaches, demonstrates a significant stride towards overcoming these obstacles. Furthermore, the integration of advanced computational methods, including machine learning, alongside the incorporation of auxiliary environmental data, marks a promising frontier for the development of more accurate, robust, and energy-efficient localization solutions. This review not only highlights the current state and challenges of USN localization algorithms but also sets the stage for future research directions, emphasizing the need for adaptive, scalable, and sustainable solutions that can navigate the complexities of the underwater domain. The convergence of interdisciplinary research efforts and technological innovations continues to push the boundaries of what is possible in underwater sensing, opening new horizons for exploration, monitoring, and the sustainable management of aquatic environments.

REFRENCES

[1] Akyildiz, Ian F., Dario Pompili, and Tommaso Melodia. "Underwater acoustic sensor networks: research challenges." *Ad hoc networks* 3, no. 3 (2005): 257-279.

[2] Erol-Kantarci, Melike, Hussein T. Mouftah, and Sema Oktug. "A survey of architectures and localization techniques for underwater acoustic sensor networks." *IEEE communications surveys & tutorials* 13, no. 3 (2011): 487-502.

[3**]** Freitag, Lee, Matthew Grund, Sandipa Singh, James Partan, Peter Koski, and Keenan Ball. "The WHOI micro-modem: An acoustic communications and navigation system for multiple platforms." In *Proceedings of OCEANS 2005 MTS/IEEE*, pp. 1086-1092. IEEE, 2005.

[4] Heidemann, John, Milica Stojanovic, and Michele Zorzi. "Underwater sensor networks: applications, advances and challenges." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 370, no. 1958 (2012): 158-175.

[5] Awan, Khalid Mahmood, Peer Azmat Shah, Khalid Iqbal, Saira Gillani, Waqas Ahmad, and Yunyoung Nam. "Underwater wireless sensor networks: A review of recent issues and challenges." *Wireless Communications and Mobile Computing* 2019 (2019).

[6] Lanbo, Liu, Zhou Shengli, and Cui Jun-Hong. "Prospects and problems of wireless communication for underwater sensor networks." *Wireless Communications and Mobile Computing* 8, no. 8 (2008): 977-994.

[7] Stojanovic, M. (2009). Underwater acoustic communication. *Wiley Encyclopedia of Electrical and Electronics Engineering*.

[8] Tuna, G., Gungor, V. C., &Potirakis, S. M. (2014). Wireless sensor networks: A survey on underwater wireless sensor networks. *Computers & Electrical Engineering*, 40(1), 216-227.

[9] Zhou, Zhong, Zheng Peng, Jun-Hong Cui, Zhijie Shi, and Amvrossios Bagtzoglou. "Scalable localization with mobility prediction for underwater sensor networks." *IEEE Transactions on Mobile Computing* 10, no. 3 (2010): 335-348.

[10] Akyildiz, Ian F., Dario Pompili, and Tommaso Melodia. "Underwater acoustic sensor networks: research challenges." *Ad hoc networks* 3, no. 3 (2005): 257-279.

[11] Erol-Kantarci, Melike, Hussein T. Mouftah, and Sema Oktug. "A survey of architectures and localization techniques for underwater acoustic sensor networks." *IEEE communications surveys & tutorials* 13, no. 3 (2011): 487-502.

[12] Freitag, Lee, Matthew Grund, Sandipa Singh, James Partan, Peter Koski, and Keenan Ball. "The WHOI micro-modem: An acoustic communications and navigation system for multiple platforms." In *Proceedings of OCEANS 2005 MTS/IEEE*, pp. 1086-1092. IEEE, 2005.

[13] Heidemann, John, Milica Stojanovic, and Michele Zorzi. "Underwater sensor networks: applications, advances and challenges." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 370, no. 1958 (2012): 158-175.

[14] Awan, Khalid Mahmood, Peer Azmat Shah, Khalid Iqbal, Saira Gillani, Waqas Ahmad, and Yunyoung Nam. "Underwater wireless sensor networks: A review of recent issues and challenges." *Wireless Communications and Mobile Computing* 2019 (2019).

[15] Lanbo, Liu, Zhou Shengli, and Cui Jun-Hong. "Prospects and problems of wireless communication for underwater sensor networks." *Wireless Communications and Mobile Computing* 8, no. 8 (2008): 977-994.

[16] Stojanovic, M. (2009). Underwater acoustic communication. Wiley Encyclopedia of Electrical and Electronics Engineering.

[17] Tuna, G., Gungor, V. C., &Potirakis, S. M. (2014). Wireless sensor networks: A survey on underwater wireless sensor networks. Computers & Electrical Engineering, 40(1), 216-227.

[18] Zhou, Zhong, Zheng Peng, Jun-Hong Cui, Zhijie Shi, and Amvrossios Bagtzoglou. "Scalable localization with mobility prediction for underwater sensor networks." *IEEE Transactions on Mobile Computing* 10, no. 3 (2010): 335-348.

[19] Peres, Rodrigo T., and Carlos Eduardo Pedreira. "A new local–global approach for classification." *Neural Networks* 23, no. 7 (2010): 887-891.

[20] Nazir, U., N. Shahid, M. A. Arshad, and S. Hussain Raza. "Classification of localization algorithms for wireless sensor network: A survey." In *2012 International conference on opensource systems and technologies*, pp. 1-5. IEEE, 2012.

[21] Han, Guangjie, Huihui Xu, Trung Q. Duong, Jinfang Jiang, and Takahiro Hara. "Localization algorithms of wireless sensor networks: a survey." *Telecommunication Systems* 52 (2013): 2419-2436.

[22] Do, Thanh-Nghi, and François Poulet. "Random local SVMs for classifying large datasets." In *Future Data and Security Engineering: Second International Conference, FDSE 2015, Ho Chi Minh City, Vietnam, November 23-25, 2015, Proceedings 2*, pp. 3-15. Springer International Publishing, 2015.

[23] Kim, Woojin, Jaemann Park, H. Jin Kim, and Chan Gook Park. "A multi-class classification approach for target localization in wireless sensor networks." *Journal of Mechanical Science and Technology* 28 (2014): 323-329.

[24] Do, Thanh-Nghi, and François Poulet. "Parallel learning of local SVM algorithms for classifying large datasets." In *Transactions on Large-Scale Data-and Knowledge-Centered Systems XXXI: Special Issue on Data and Security Engineering*, pp. 67-93. Springer Berlin Heidelberg, 2017.

[25] Han, Guangjie, Jinfang Jiang, Lei Shu, Yongjun Xu, and Feng Wang. "Localization algorithms of underwater wireless sensor networks: A survey." *Sensors* 12, no. 2 (2012): 2026-2061.

[26] Suomela, Jukka. "Survey of local algorithms." *ACM Computing Surveys (CSUR)* 45, no. 2 (2013): 1-40.

[27] Li-qiang, Chen. "Distributed Localization Algorithm in Wireless Sensor Network." In *2013 International Conference on Computational and Information Sciences*, pp. 1441-1444. IEEE, 2013.

[28] Bischl, Bernd, Julia Schiffner, and Claus Weihs. "Benchmarking local classification methods." *Computational Statistics* 28, no. 6 (2013): 2599-2619.